PETROLOGICAL STUDIES IN THE ORDOVICIAN OF NEW SOUTH WALES. III.

THE COMPOSITION AND ORIGIN OF THE UPPER ORDOVICIAN GRAPTOLITE-BEARING SLATES.

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(Four Text-figures.)

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Contents.

I. INTRODUCTION.

Some years ago, when making a detailed study of the Ordovician rocks at Cooma, I had occasion to analyse a graptolite-bearing black slate of Upper Ordovician age. A number of more highly altered pelitic sediments previously analysed showed a very uniform composition, with a silica range of about 54–61%, and it was with some surprise that I found that this less altered type contained over 80% of silica. Two other rocks, on approximately the same stratigraphical horizon and from widely separated parts of the same district, also proved, on analysis, to be highly siliceous, and this led to an investigation of the graptolite-bearing slates from other localities in New South Wales. The results of this study are presented in the present paper.

II. THE GRAPTOLITE-BEARING SLATES.

1. *General Description.*

In every area where these rocks occur (see map, Fig. 1) there is a remarkable lithological uniformity and they are found either as black or dark bluish-grey slates, as light grey or white fissile slates or as cherts. The graptolites are often very well preserved and appear either as black carbonaceous films, as white micaceous films or as reddish-brown films of iron oxide. The last type of preservation seems to be more common in the light coloured, fissile varieties which have probably been oxidized and leached; except for a lower carbon content they do not differ markedly in composition from the black slates with which they are usually interbedded (see Table 2, Analyses C and L).

The slates are usually in a low grade of regional metamorphism, and a well-marked slaty cleavage, particularly in the light coloured leached types, is often well developed. Slate quarries have been worked at Ariah Park, near Temora, and the Yalgogrin occurrence was investigated with a view to exploitation as roofing slates. Sometimes the slates are much veined with quartz and, when near a granite contact, chiastolite is

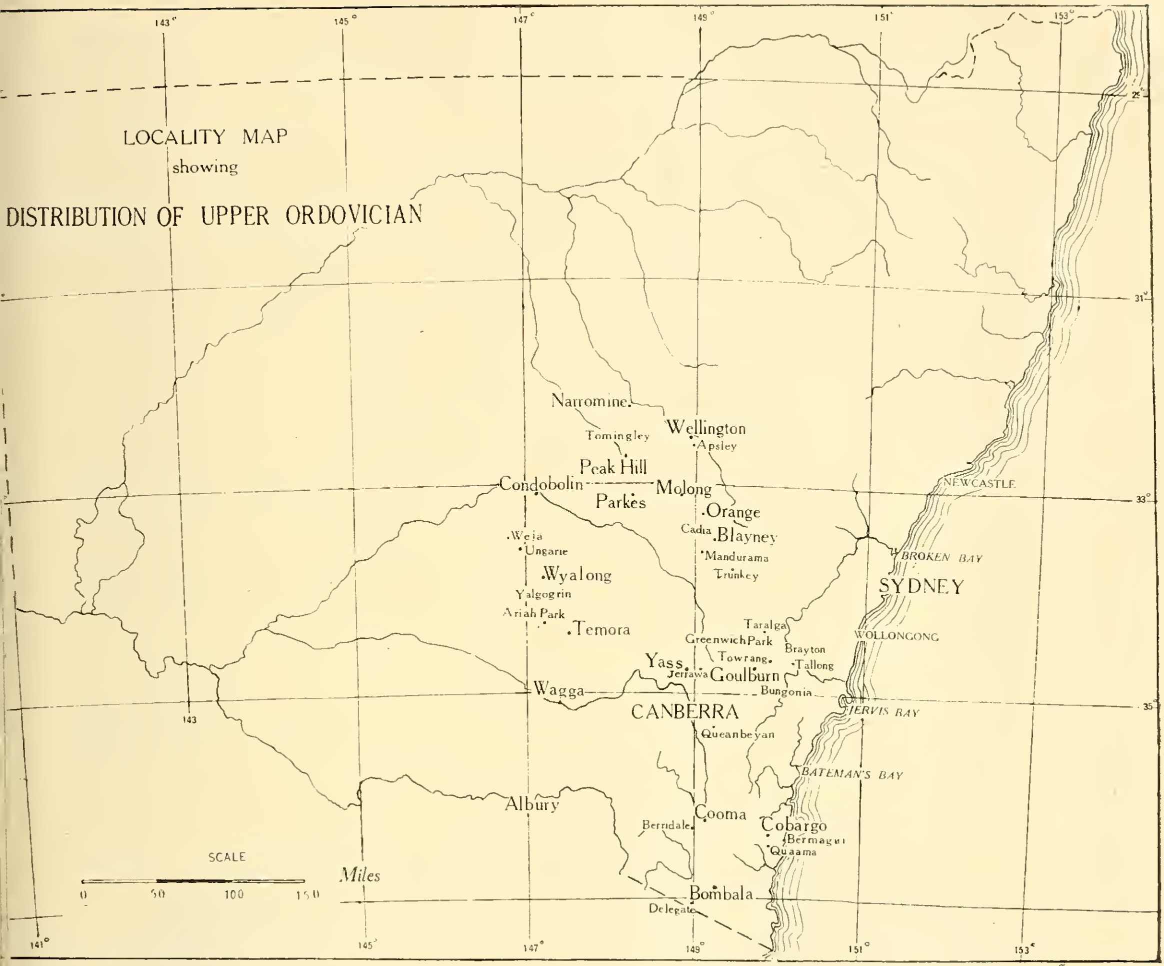

Fig. 1.

often developed. In the chiastolite slates graptolites are easily recognizable and appear to be preserved in a white micaceous material.

Although the slates have been examined under very high magnification, much of the material is not resolved by the microscope. The rocks are often banded with finely carbonaceous seams alternating with carbon-free or carbon-poor bands (Fig. 2B). The non-carbonaceous seams appear to consist of tiny flakes of sericite, small zircons, needles of rutile and occasional tiny grains of quartz in a faintly green almost isotropic base which is not completely resolved. Minute Y-shaped bodies sometimes occur, and these may possibly represent sponge-spicules, whilst tiny rounded patches of chalcedony are doubtfully interpreted as radiolaria. Other, less regular, patches of radiating chalcedony have also been noted, and it is possible that some of the base may consist of this mineral. This chalcedony and the occasional minute quartz veins point to secondary silicification, but it appears to be an internal rearrangement of a primary constituent. The amount of quartz and sericite varies in the different slates and when present as distinct grains the quartz often shows a curved fracture.

Biotite is developed in some of the slightly metamorphosed types and chiastolite and incipient cordierite are not uncommon when the slate occurs near a granite contact (Fig. 2C).

Reference to Table 2 will show that slates from seven widely separated localities in New South Wales show marked chemical similarity. Though there is a range of some 10% of silica, it is always very high, and with the possible exception of Analysis A, there is every reason to believe that no silica has been added from an outside source. The analyses are arranged in order of decreasing silica without reference to their locality, and it can be seen that there is a slight increase of alumina and potash accompanying the decrease in silica and that the amount of ferric oxide is a little variable, but for all these differences, the variations are only minor ones and it can be seen that the slates all belong to a single rock-series.

The graptolite-bearing rocks are interbedded with buff coloured slates of slightly coarser texture or with more sandy types which range from fine-grained quartzites to medium-grained sandstones coloured white, buff, red, grey or black. In these, negative crystals of pyrites are not uncommon.

Near Tallong, in the Shoalhaven Gorge at Badgery's Crossing, perfectly preserved graptolites occur as black carbonaceous films in a dark grey quartzite. Under the microscope this rock is seen to consist of somewhat rounded and sub-angular quartz grains in a matrix of sericite, chlorite and some isotropic material. Zircons and rutile can be recognized. In rather similar rocks at Cooma (Joplin, 1942, p. 160) occasional small grains of oligoclase-andesine ($Ab_{70}An_{30}$–$Ab_{65}An_{32}$) occur with rounded or sub-angular grains of quartz. The occurrence of fairly fresh felspar in these rocks suggests wind action, ice action, volcanic action or close proximity to the source of supply. The conchoidal fracture of the quartz grains (Fig. 2A) may be interpreted as the result of sub-aerial weathering and temperature changes (Waterhouse and Browne, 1929) or as the result of shattering by volcanic activity (Pirsson, 1915).

2. *Stratigraphical Position.*

Reference to Table 1 will show that Upper Ordovician graptolites have been recorded from a number of widely separated localities in New South Wales, but it will also show that intensive collecting and detailed descriptive work has been confined only

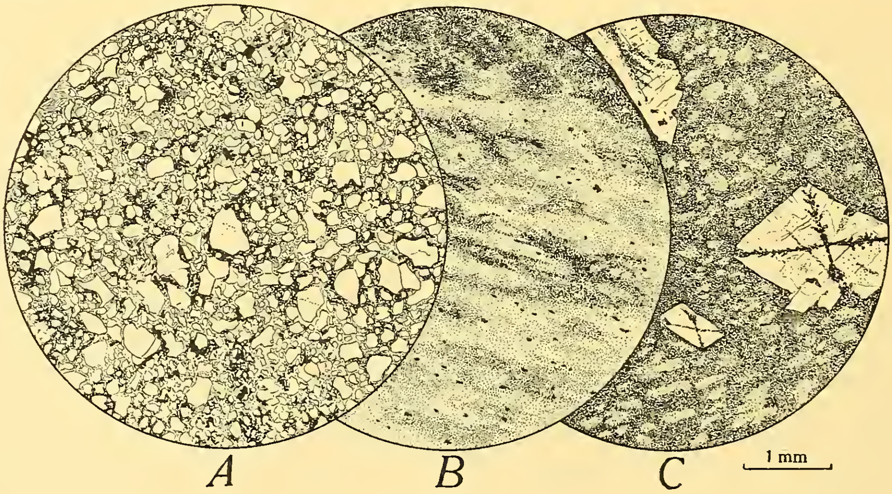

Fig. 2.

A. Low-grade psammite in Coolringdon Beds on Berridale Road, near Slack's Creek, SW. of Cooma. The rock shows rounded and sub-angular grains in an argillaceous and ferruginous matrix. Note curved fracture in quartz grains, and small patches of clastic mica. × 12.

B. Siliceous slate with carbonaceous bands from Wambrook Creek at crossing of Adaminaby Road, W. of Cooma. Note tiny clastic grains of quartz and iron ore. × 12.

C. Chiastolite-slate, Gygederick Hill near Berridale. Former slight schistosity indicated by orientation of incipient cordierite crystals. The groundmass consists mainly of finely divided carbonaceous material and quartz. × 12.

Reprinted from these PROCEEDINGS, lxvii, 1942, 161.

TABLE 1

DISTRICT.	LOCALITY.	ROCK TYPE.	% SILICA.	DISTANCE FROM IGNEOUS CONTACT.	GRAPTOLITES RECORDED.	REFERENCES.
PEAK HILL.	Tomingley.				4 genera, 7 species.	Dun (1898); Hall (1902).
WELLINGTON.	Wellington.	Chert.		5-6 miles from granite.	1 genus, 5 species.	Keble and Sherrard (1938); Basnett and Colditz (1944); Jones (1935).
	Apsley.	Chert.		About 8 miles from granite.	3 genera, 5 species.	Keble and Sherrard (1938); Basnett and Colditz (1944); Jones (1935).
ORANGE.	Cadia.	Slate.		?	1 genus.	Smith (1899); Hall (1902).
	Mandurama.	Chert.		?	2 genera, 4 species.	Hall (1900, 1902).
WYALONG-CONDOBOLIN.	Weja.	Black slate.	78·89	?	Graptolites present not determined.	
	Ungarie.	?	81·46	?	?	*A. R. Dept. Mines, N.S.W.*, 1920.
TEMORA.	Yalgogrin.	Bluish - grey slate (bleached).	82·62 84·03	2 miles from granite.	3 genera.	Harper (1921); *A. R. Dept. Mines, N.S.W.*, 1920.
	Ariah Park.	Dark fissile slate.		?	Graptolite impressions too imperfect for identification.	Harper (1921).
GOULBURN.	Tallong.	Black slate often with incipient chiastolite.	86·22	Analysed rock about 1 mile from granite.	2 genera.	Woolnough (1909); Naylor (1935*a*, 1938).
	Brayton - Greenwich Park.	Grey and bluish slates, shales and claystones.		Up to 2 miles from granite.	3 genera, 8 species.	Naylor (1935*a*, 1938).
	Towrang.	Grey-blue slates, shales and claystones.		1-2 miles from granite.	7 genera, 19 species.	Naylor (1935*a*, 1938).
	Bungonia-Tolwong.			?	6 genera, 9 species.	Carne (1911); Hall (1909, 1920); Naylor (1935*a* and *b*).
	Taralga.	Greyish - blue silicified slate.		?	2 genera, 6 species.	Naylor (1937, 1938).
	SW. of Goulburn.			?	3 genera, 4 species.	Naylor (1938).
CANBERRA.	Queanbeyan.	Black and light grey slate (bleached).			3 genera, 6 species.	Harris and Keble (1929).
YASS.	Jerrawa.	Blue-grey slate.		About 3 miles from granite.	4 genera, 16 species.	Sherrard (1936, 1939, 1942).
	Yass River.	Blue-grey slates sometimes silicified.	87·13	About 5 miles from granite.	9 genera, 30 species.	Sherrard (1936, 1939, 1942); Sherrard and Keble (1937).
WAGGA.	Wagga.	Chiastolite slate.	78·82	At granite contact.	Graptolites present not determined.	
COOMA.	Wombrook Ck.	Dark grey phyllite.	78·45	About 2 miles from granite.	4 genera, 7 species.	Laseron (1909); Brown (1914); Joplin (1942).
	Berridale.	Chiastolite slate.	80·37	At granite contact.	1 genus.	Browne (1914, 1943); Joplin (1942).
	Cottage Ck.	Black and light grey slate (bleached).	85·96	About 2 miles from granite.	1 genus.	Browne (1931, 1943); Joplin (1942).
BOMBALA-DELEGATE.	Stockyard Ck.				5 genera, 10 species.	Dun (1897); Hall (1902).
	Currowang.				3 genera.	Dun (1897); Hall (1902).
	Tingaringi.				2 genera, 3 species.	Dun (1897); Hall (1902).
	Lawson.	Black slate.			4 genera, 5 species.	Dun (1897); Hall (1902).
SOUTH COAST.	Cobargo.	Black slate (north). Bleached slate (east).	77·32	Less than 1 mile from granite.	3 genera, 4 species.	Browne (1914); Brown (1933).
	Quaama.	Black slate.	83·04	Less than 1 mile from granite contact.	2 genera.	Brown (1933).

to a few areas. In consequence of this, no zoning is possible at present, and as several graptolite zones are possibly represented among the collections from a single locality, it was considered useless to publish lists of the various species; furthermore it was also impossible to tell precisely from which graptolite-horizon each analysed specimen had been taken, and it seems likely that the analysed rocks listed in Table 2 represent a number of different horizons in the Upper Ordovician sequence. In Table 1 a complete list of publications for each locality is given, and though some of these refer to general information concerning the slates, most deal with the graptolites, and to these the reader is referred for detailed information on the fauna. Most of these references have been compiled by Keble and Benson (1939), but Table 1 has been included in the present paper since it has been arranged in such a way that all available information about a single locality may be seen at a glance and may be compared with available information from other Upper Ordovician localities.

Schists believed to be of Ordovician age occur at Cooma, Albury, Jingellic, Junee Reefs and possibly in the Trunkey and Yalgogrin districts. At Cooma these occur in close proximity to the Upper Ordovician graptolite-bearing slates and there appears to be a gradual progressive metamorphism from slates into schists. In the metamorphic area of North-East Victoria, of which the Albury district is the northern extension, a similar progressive change has been observed from graptolite-bearing Upper Ordovician slates into high grade schists, and on this account, the schists have been regarded as Upper Ordovician sediments (Howitt, 1889; Browne, 1914, 1929, 1943; Tattam, 1929; Joplin, 1942, 1943). Reference to Tables 2 and 3 will show that the slates and schists form two chemically distinct rock-series, and furthermore, in the only locality in New South Wales, namely Cooma, where both series have been studied, they appear to occupy distinct stratigraphical horizons and no interbedding of the one type with the other has ever been observed. In this area the siliceous slates have been termed the Coolringdon Beds and the aluminous schists the Binjura Beds (Joplin, 1942, 1943). Interbedded with the schists of the Binjura Beds, however, sandy schists, containing some plagioclase felspar, often occur and these have a composition rather similar to the siliceous slates (Joplin, 1942, p. 161, Table 2, Anal. IV).

If the schists are of Ordovician age and are not interbedded with the siliceous slates, then they must be either above or below them. According to Dr. W. R. Browne's interpretation of the structure (Browne, 1943) the Binjura Beds overlie the Upper Ordovician slates.

My interpretation of the structure at Cooma (Joplin, 1943) places the Coolringdon Beds above the Binjura Beds and below the Bransby Beds—a series consisting of porphyries, rhyolites, tuffs and limestones (see Fig. 3).

Unfortunately the isoclinal folding and the possibility of overthrusting at Cooma make the interpretation of the structure very difficult, and as the Coolringdon and Binjura Beds have not yet been found together elsewhere in New South Wales, only indirect evidence can be used in interpreting the structure. At Trunkey, Raggatt (1934) finds black slates above schists, but as graptolites have not been found, their age is not certain. It is hoped that graptolites may be found at Jingellic where the Binjura schists are highly carbonaceous and in a comparatively low grade of metamorphism, but in the meanwhile the relative age of the Coolringdon and Binjura Beds must remain in doubt.

III. ORIGIN OF THE BLACK SLATES OF NEW SOUTH WALES.

1. *Possibility of Silicification.*

The occurrence of quartz veins and the not infrequent proximity of granite (see Table 1) immediately raises the question of silicification of the black slates. In fact many of the siliceous slates have been described as "silicified slates" and there is no doubt that local silicification has taken place in some areas. In selecting material for analysis, however, care was taken to avoid any specimens containing quartz veins or any apparent addition of silica from an outside source. As pointed out above, a microscopic examination sometimes revealed that there had been a slight silicification which could be attributed to an internal arrangement of the original silica of the rock.

TABLE 2.

	A.	B.	C.	D.	E.	F.	G.	H.	I.	J.	K.	L.
SiO_2	87·13	86·22	85·96	84·03	83·04	82·62	81·46	80·37	78·89	78·82	78·45	77·32
Al_2O_3	8·99	8·91	8·49	9·77	9·57	10·49	10·08	10·04	13·10	12·25	12·92	14·43
Fe_2O_3	0·17	0·24	0·33	0·35	0·77	0·45	0·15	0·35	0·68	0·64	1·48	0·48
FeO			0·19				0·27	1·44			0·95	
MgO	0·32	0·28	0·65	0·36	0·35	0·44	0·58	0·57	0·30	0·28	0·36	0·61
CaO	tr.	abs.	0·10	0·12	0·05	0·18	0·54	0·37	0·18	abs.	0·19	abs.
Na_2O	0·10	0·19	0·48	2·38	0·30	n.d.	0·18	0·93	0·38	0·26	0·23	0·29
K_2O	1·56	1·57	1·91		1·87	n.d.	2·16	2·09	2·09	3·27	2·39	3·11
H_2O+	0·98	1·11	1·37	2·44	0·91	n.d.	4·08	2·44	1·01	1·52	2·32	1·90
H_2O-	0·18	0·09	0·07		0·08	n.d.	0·12	0·17	0·23	0·22	0·25	0·12
TiO_2	0·32	0·49	0·49	0·55	0·52	0·42	0·45	0·52	0·64	0·71	0·42	0·80
P_2O_5	0·15	0·11	0·07	n.d.	0·24	n.d.	n.d.	0·19	abs.	0·01	0·06	0·28
MnO	tr.	tr.	tr.	n.d.	tr.	n.d.	n.d.	tr.	tr.	tr.	0·01	tr.
C	0·38	1·51	0·04	n.d.	1·88	n.d.	n.d.	1·17	2·15	1·67	n.d.	0·18
S	0·07	0·01	0·05	n.d.	0·13	n.d.	n.d.	n.d.	0·14	0·08	n.d.	0·09
	100·35	100·73	100·20	100·00	99·71	—	100·07	100·65	99·81	99·73	100·03	99·61
Sp. Gr.	2·60	2·66	2·68	—	2·69	—	—	2·68	2·63	2·60	2·71	2·62

A. Graptolite-bearing Black Slate. Por. 81, Par. of Mundoonen, Loc. 13 (Sherrard, 1942), Yass River. Anal. G. A. Joplin.
B. Graptolite-bearing Black Slate. Above Digger's Ck., Por. 95, Par. of Bumballa, near Tallong. Anal. G. A. Joplin.
C. Graptolite-bearing Grey Slate. Ingram's Ck., Por. 42, Par. of Arable, south of Cooma. Anal. G A. Joplin. PROC. LINN. SOC. N.S.W., 67, 161.
D. Graptolite-bearing Slate. North of Yalgogrin. *A. R. Dept. Mines, N.S.W.*, 1920: 125.
E. Graptolite-bearing Black Slate. Por. 17, Par. of Cadjangarry, Pipeclay Ck., near Quaama. Anal. G. A. Joplin.
F. Graptolite-bearing Slate. North of Yalgogrin. Ibid.
G. Slate. Merringreen, Ungarie. Ibid.
H. Chiastolite-slate with graptolite remains. Gygederick Hill, near Berridale. Anal. G. A. Joplin. PROC. LINN. SOC. N.S.W., 67, 161.
I. Graptolite-bearing Black Slate. Three miles north of Weja. Anal. G. A. Joplin.
J. Chiastolite-slate with graptolite remains. 20 chs. west of Moorong Trig., Wagga Common, Par. of Uranquinty. Anal. G. A. Joplin.
K. Dark Grey Slate (slightly micaceous). Wambrook Ck. at crossing of Adaminaby Road, west of Cooma. Anal. G. A. Joplin. Ibid.
L. Graptolite-bearing Grey Slate. Bermagui Road, Por. 176, Par. of Bermaguee, east of Cobargo. Anal. G. A. Joplin.

TABLE 3.

	COOMA.								ALBURY.		TALLANGATTA.		DARGO.		ENSAY.		"INDICATORS."	
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*
SiO_2	57·07	54·18	58·87	56·40	54·63	56·05	59·05	61·13	55·49	59·42	52·91	56·52	51·33	62·28	55·94	56·33	58·66	63·74
Al_2O_3	20·95	25·48	21·23	23·20	25·35	24·91	22·95	23·43	24·45	21·44	24·49	23·13	25·69	20·16	23·39	22·94	23·26	19·91
Fe_2O_3	4·27	2·99	2·47	1·30	2·40	1·22	1·48	0·09	2·21	1·09	5·45	1·96	4·80	0·53	0·45	2·19	4·28	4·07
FeO	2·42	3·08	4·05	5·22	4·64	4·76	5·16	4·84	4·92	5·23	1·50	5·09	1·07	3·84	4·69	4·54	0·38	0·45
MgO	3·08	3·13	2·98	3·24	2·75	2·51	2·37	1·99	2·88	2·53	1·80	2·82	2·72	2·54	3·58	3·27	2·41	2·10
CaO	0·14	0·41	0·12	0·63	0·65	0·51	0·65	0·63	0·35	0·11	0·35	0·39	0·25	0·82	0·81	0·25	abs.	abs.
Na_2O	0·42	0·73	0·60	0·61	0·62	1·06	0·81	1·08	0·54	0·66	1·08	0·24	0·77	1·29	1·45	0·88	0·49	0·55
K_2O	4·50	5·70	5·73	5·65	6·28	6·12	5·85	5·84	5·21	6·14	6·60	6·14	6·13	6·40	6·98	6·10	3·44	3·89
H_2O+	3·71	2·88	2·59	2·77	1·25	1·23	1·17	0·26	2·09	1·82	3·81	2·27	6·73	1·86	3·17	3·07	5·60	4·49
H_2O-	1·03	0·48	0·22	0·30	0·26	0·22	0·18	0·20	0·07	0·19	0·61	0·20			0·43	0·80	1·02	0·47
TiO_2	0·82	0·73	0·84	0·57	0·86	0·86	0·68	0·72	0·78	0·96	0·83	1·17	0·43	0·17	—	—	0·97	0·79
P_2O_5	0·06	0·07	0·05	0·06	0·20	0·14	0·18	0·24	0·20	0·04	0·10	0·22	—	—	0·10	0·13	abs.	tr.
MnO	0·05	0·03	0·02	0·01	0·05	0·11	0·05	0·09	0·06	0·05	0·06	0·06	—	—	—	tr.	—	—
ZrO_2	n.d.	n.d.	0·02	0·05	0·15	0·09	0·19	0·16	n.d.	n.d.	—	—	—	—	—	—	—	—
BaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·06	0·11	—	—	—	—	—	—
CO_2	0·74	—	—	—	—	—	—	—	0·30	abs.	—	—	—	—	—	—	—	—
C	1·33	0·34	0·16	0·51	—	—	—	—	0·03	—	0·19	—	—	—	—	—	—	—
Cl	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	100·59	100·23	99·95	100·52	100·09	99·79	99·86	100·70	99·61	99·68	99·78	100·32	99·98	100·04	100·99	100·50	100·51	100·57
Less O for Cl ..	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0·03
																		100·54
Sp. Gl.	2·76	2·80	2·78	2·85	2·83	2·85	2·82	2·81	2·83	2·82	—	—	2·69	2·74	2·78	2·75	—	—

a. Chlorite-sericite-phyllite. West of Slack's Creek, Por. 154, Par. of Coolringdon. Anal. G. A. Joplin. PROC. LINN. SOC. N.S.W., 67 : 164.
b. Chlorite-sericite-phyllite. About ½ mile east of McCarthy's Crossing, Por. 144, Par. of Coolringdon. Anal. G. A. Joplin. Ibid.
c. Plicated Mica-schist. Slack's Creek at crossing of Dry Plain Road. Anal. G. A. Joplin. Ibid.
d. Knotted Andalusite-schist. Slack's Creek, Por. 137, Par. of Binjura. Anal. G. A. Joplin. Ibid.
e. Spotted Granulite. Por. 212, Par. of Binjura. Anal. G. A. Joplin. Ibid., p. 181.
f. Mottled Gneiss (Paragneiss). Spring Creek, Por. 212, Par. of Binjura. Anal. G. A. Joplin. Ibid.
g. Mottled Gneiss (Paragneiss). Spring Creek, Por. 212, Par. of Binjura. Anal. G. A. Joplin. Ibid.
h. Mottled Gneiss (Paragneiss). Spring Creek, Por. 212, Par. of Binjura. Anal. G. A. Joplin. Ibid.
i. Knotted Schist. Hamilton Trigonometrical Station, Por. 275, Par. of Jindera. Anal. G. A. Joplin.
j. Mottled Gneiss (Paragneiss). Eastern Hills, Por. 74, Par. of Albury. Anal. G. A. Joplin.
k. Slate. Eastern slopes of Mt. Wagra, near Tallangatta, Victoria. Anal. C. A. Tattam, *Geol. Surv. Vict.*, Bull. 52, 1929 : 35.
l. Andalusite Hornfels. Noorongong. Anal. C. A. Tattam. Ibid.
m. Argillite. Waterford, Dargo Road at Mitchell River Crossing. Anal. A. W. Howitt. *Trans. and Proc. Roy. Soc. Vict.*, 23, 1887 : 130
n. Hornfels. Orr's Gully. Anal. A. W. Howitt. Ibid., 23 : 133.
o. Phyllite. Ensay Area. Anal. A. W. Howitt. Ibid., 22, 1886 : 68.
p. Metamorphic Gneiss. Little River, Ensay. Anal. A. W. Howitt. Ibid., 22 : 75.
q. Lower Ordovician Slate "Indicator". Champion Reef, Wedderburn, Victoria. Anal. P. G. W. Bayley. *Mem. Geol. Surv. Vict.*, No. 10 : 14.
r. Lower Ordovician Slate. Baker's Mine, Wedderburn. Anal. P. G. W. Bayley. Ibid.

Normal pelites arranged in each district in order of increasing metamorphism.

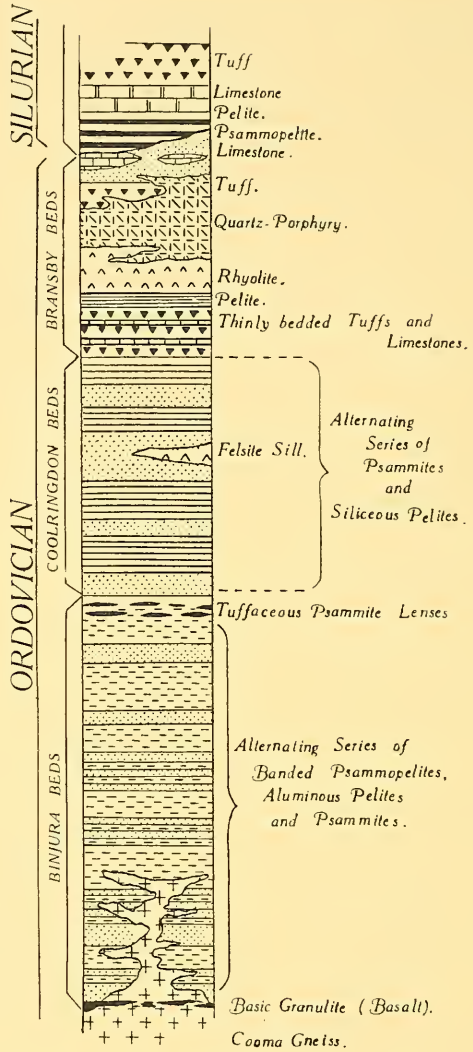

Fig. 3.

Columnar section showing approximate sequence of the Ordovician as exposed in the Cooma Region. The thickness of beds has not been measured and the section is therefore not drawn to scale. Note presence of tuffs above and below the Coolringdon Beds and rhyolites in the Bransby Beds.

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As previously indicated, the two chemically distinct rock series listed in Tables 2 and 3 are never found interbedded, but there is a close field association at Cooma, in certain areas of North-East Victoria, and possibly in the Trunkey district of New South Wales (Raggatt, 1934; Browne, 1935). As Table 3 lists the only normal pelitic rocks anywhere in the vicinity of the siliceous slates, it must be assumed that if the latter are the result of silicification then the normal pelite was the parent rock.

In the first place it would seem to be rather a coincidence that all the normal pelites were silicified to about the same degree and that no gradations in the progressive silicification occur. It is true that the slates show a variation of about 10% of silica and that there is a sympathetic variation in the other oxides, but apart from other differences there is a large gap between the series that could reasonably be expected to be filled if progressive silicification had occurred. There is sometimes a suggestion that the presence of carbon promotes the addition of silica and if there is no further selection than this, then all other oxides should be present in about the same amount as those of the original rock. If any other single oxide were selectively replaced, then it must have been necessarily an oxide present in large amount, for some 25% of silica must have been added. Actually only alumina could have been present in sufficient amount to meet this requirement, and an inspection of the analyses will show that there is no justification for such an assumption. Assuming some constituent to have remained constant, it would be possible to calculate what has been added to or subtracted from the aluminous pelite in order to convert it into the siliceous pelite, but this would lead to the dangerous assumption that one rock had actually been derived from the other. In this case no such fact is known and actually with sufficient manipulation of chemical analyses a rock of any type might be calculated into another. Thus, while a two-way passage of oxides is not denied, it is felt that there is no reasonable chemical evidence for such an assumption, and that such calculations might prove a very fallacious argument. It is possible to assume, however, that there had been no selection in the silicification, and if such were the case then the other oxides of the slates should be present in the same ratios as those of the normal pelites. To test out this assumption an A-F-C diagram was constructed with A = the molecular proportion of alumina after satisfying alkalis, with C = the molecular proportion of lime and F = the molecular proportion of magnesia plus total ferrous oxide after satisfying titania for ilmenite. As the relative amounts of ferrous and ferric oxide vary with the degree of metamorphism, the making of magnetite brought out untrue differences between rocks that had approximately the same total iron, and it was considered that a more valid comparison could be made between the analyses if ferric oxide was reduced and added to ferrous oxide. As sulphur has been estimated only in a few of the analyses, pyrites was not calculated. Further, it was considered inadvisable to satisfy phosphorus pentoxide with lime for apatite, as it seems not unlikely that the phosphorus may be present in some of the low grade rocks as vivianite or some earthy form. Furthermore, phosphorus pentoxide has not been determined in some of the older analyses of rhyolites and tuffs, with which the analyses of the slates are compared.

Inspection of the triangular diagram (Fig. 4) will show that the normal pelites occupy a very restricted field and that the field of the siliceous pelites, though not quite so well defined, is distinct from that of the other type. As SiO_2 has not been taken into account in this diagram, it has been possible to compare the ratios of Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O and TiO_2 in both rock series, and there is thus evidence for the conclusion that the ratios of the various oxides in the two rock-series differ and that there is no evidence for the assumption that the slates are silicified normal pelites.

2. *Origin of the Siliceous Material.*

If the slates are not silicified slates but siliceous slates, then the origin of such a sediment must be considered. Inspection of the analyses of silts and fine, deep-water sediments (Clarke, 1916; Twenhofel, 1926) throws no light on the matter, but Fig. 4 shows that a number of rhyolites and rhyolite tuffs compare with the slates in the ratios of their respective oxides. Although only twenty-eight analyses of the lavas and tuffs have been plotted, the analyses have been chosen from various parts of the world, and although the area enclosed within the dotted line is not strictly the field of the rhyolites, it possibly represents that of most normal types. Reference to Fig. 4 shows that the field of the siliceous slates falls within the less well defined one of the rhyolites and rhyolitic tuffs. Moreover, No. 12, a rhyolite from the Ordovician at Cooma, falls within the slate field.

It is therefore suggested that the slates consist largely of redistributed rhyolite tuff.

In describing the slates it was mentioned that they were interbedded with more sandy types containing sub-angular quartz grains and occasional grains of andesine (Fig. 1A), and such features would be in accord with the suggestion of a pyroclastic origin. Actually a little tuffaceous material of a coarser nature has been recognized in the Binjura Beds and in the Bransby Beds of the Cooma district (Joplin, 1942, 1943), but this appears small by comparison with the great amounts of volcanic dust that must be postulated for the formation of the siliceous slates.

Fig. 4.

A-F-C diagram showing plots of analyses of siliceous slates (A, B, etc., Table 2), of normal pelites (a, b, etc., Table 3) and of rhyolitic tuffs (triangles) and rhyolites (circles) as listed below.

1. Volcanic Tuff. Tooloom, N.S.W.—In W.T., No. 37 : 801.
2. Brisbane Tuff. Queensland.—C. Briggs, 1929, *Proc. Roy. Soc. Qd.*, 40 : 156.
3. Rhyolite Tuff. Westmoreland, England.—In W.T., No. 26 : 801.
4. Liparite Tuff. Eritrea.—In W.T., No. 33 : 801.
5. Liparite Tuff. Sardinia.—In W.T., No. 30 : 801.
6. Rhyolite Ash. Montana, U.S.A.—In W.T., No. 4 : 797.
7. Rhyolite Tuff. Montana, U.S.A.—In W.T., No. 5 : 799.
8. Rhyolite Tuff. (Lake bed deposit), Colorado, U.S.A.—In W.T., No. 10 : 799.
9. Rhyolite Tuff. Oregon, U.S.A.—In W.T., No. 14 : 799.
10. Rhyolite Tuff. California, U.S.A.—In W.T., No. 18 : 799.
11. Rhyolite Tuff. California, U.S.A.—In W.T., No. 19 : 799.

12. Rhyolite. Cooma district, N.S.W.—G. Joplin, 1943, Proc. Linn. Soc. N.S.W., 68 : 165.
13. Rhyolite Glass. Gloucester, N.S.W.—In W.T., No. 42 : 97.
14. Rhyolite. Esk, Queensland.—C. Briggs, 1929, *Proc. Roy. Soc. Qd.*, 40 : 156.
15. Rhyolite. Hauraki, N.Z.—In W.T., No 3 : 107.
16. Rhyolite. Hauraki, N.Z.—In W.T., No. 45 : 97.
17. Rhyolite. Hauraki, N.Z.—In W.T., No. 95 : 91.
18. Rhyolite Perlite. Waiau Valley, Hauraki, N.Z.—In W.T., No. 101 : 72.
19. Rhyolite. Tardree, Ireland.—F. H. Hatch, 1914, The Petrology of the Igneous Rocks : 262.
20. Rhyolite (altered). Hungary.—In W.T., No. 29 : 801.
21. Rhyolite. Hungary.—In W.T., No. 28 : 801.
22. Rhyolite. Hungary.—In W.T., No. 58 : 87.
23. Rhyolite. Japan.—In W.T., No. 39 : 97.
24. Rhyolite. California, U.S.A.—In W.T., No. 19 : 83.
25. Rhyolite. California, U.S.A.—In W.T., No. 18 : 81.
26. Rhyolite (altered). Idaho, U.S.A.—In W.T., No. 9 : 799.
27. Pumice. Katmai, Alaska.—C. Fenner, 1926, *J. Geol.*, 34 : 695.
28. Pumice. Katmai, Alaska.—C. Fenner, 1926, ibid., 34 : 695.

Above, it was mentioned that the graptolites sometimes occur in cherts, and it is pertinent to note that this rock type is not infrequently of a tuffaceous origin. A good example of chert formed in this way may be seen at Manildra, New South Wales (Joplin and Culey, 1937) where there is a gradation from fossiliferous Silurian breccias, through coarse and fine tuffs into cherts. Though these are of Silurian age they bear a strong lithological resemblance to the Wellington cherts which contain Upper Ordovician graptolites (Sherrard and Keble, 1928). It has also been suggested that the fine banded cherts of the Upper Coal Measures in New South Wales are finely divided tuffaceous material (David, 1907).

3. *Amount of Volcanic Ash available for the Formation of Slates.*

If it be assumed that the Upper Ordovician slates are deposits of volcanic ash or dust, then it must be concluded that tremendous quantities of such pyroclastic material were available. Possibly some of the shales may represent admixtures with normal clastic sediments, but the bulk of the material must be presumed to be of volcanic origin. Siliceous waters associated with the volcanic activity may have played a part in silicifying the ash deposits and any normal admixed clastic material.

The great bentonite deposits of the Upper Ordovician of North America (Nelson, 1922) are believed to represent ash deposits the volume of which has been estimated as about 66 cubic miles. Nelson suggests that the source may have been a volcanic island off the peninsula separating the Lowville Sea from the Palaeozoic Atlantic Ocean.

In reporting on the great Katmai eruption of 1912, Martin (1913) has given a graphic description of what he considers to be "the most tremendous volcanic explosion known in history". Ash fell at a distance of 900 miles from the volcanic centre, and the suspension of dust in the air caused complete darkness over an area of several thousand square miles. It is estimated that about five cubic miles of material was ejected from Katmai. According to Fenner (1925), the pyroclastic material consists largely of fragments of glass which he believes to have been cemented as a result of cohesion due to heat. Marshall (1935) postulates a similar origin for the ignimbrites which cover large areas in the North Island of New Zealand, and regarding their origin he states "they are thought to have been deposited from immense clouds or showers of intensely heated but generally minute fragments of volcanic magma". In comparing the volume of material ejected from Katmai with other great eruptions that have taken place in historical time, Martin states that a similar volume of five cubic miles was emitted from Krakatau, whilst the explosive eruption of Tomboro, an island near Java, produced an ash shower variously estimated as representing 28·6 to 50 cubic miles of material. Capps (1916) has shown that a great eruption in the Upper Yukon ejected 10 cubic miles of ash which was spread over a minimum area of 140,000 square miles, the thickness ranging from 300 feet near the volcanic centre to about an inch at the edge of the deposit. He considers that wind had helped to carry the ash a distance of some 450 miles.

The magnitude of these eruptions shows that the suggested pyroclastic origin of the New South Wales Upper Ordovician slates, though speculative, is not impossible.

4. *The Occurrence of Lavas and Ash in the Ordovician Sequence Elsewhere.*

As shown above, the great bentonite deposits of Tennessee, Kentucky and Alabama, and even further west (Nelson, 1922; Twenhofel, 1926; Schuchert and Dunbar, 1933), are ash beds, possibly rhyolitic ash now converted into leverrierite or some other clay-mineral having a composition very different from the original material. The horizon of this material is in the Middle Ordovician near the base of the Upper Ordovician on and below that of the Trenton limestone.

In Britain, rhyolites and rhyolitic ash make up a large part of the Welsh succession (Lake and Reynolds, 1912; Gregory and Barrett, 1931; Elles, 1940) and in the English Lake district (Bailey and Weir, 1939; Stamp, 1923; Hutchings, 1892) ash slates, tuffs and andesites occur in the Bala Series which make up the Upper Ordovician in that part of Britain.

When such outbursts of volcanic activity characterized the Ordovician in other parts of the world, it would be strange if Australia should have been exempt from such activity.

IV. Conditions Necessary for the Accumulation of Black Shales.

Writing on the association of graptolites with the black shales, Ruedemann (1934) points out that "no other fossil fauna is so highly restricted to a single definite rock facies", and as this rock facies is the subject of the present paper, it seems pertinent to examine the various hypotheses put forward to account for the accumulation of these black sediments with their characteristic fauna.

1. *Earlier Hypotheses.*

It is generally agreed that the black carbonaceous material of the shales has been derived from the decay of masses of seaweed to which the graptolites were either attached or associated, and the Palaeozoic plankton has been compared to that found in the modern sargasso-seas, but there is no consensus of opinion as to whether the plankton is capable of sinking to the bottom of the ocean or whether it dies and decays on the surface or is carried either alive or dead into the quiet embayments and shallower seas as the result of storms.

On the assumption that the shales and fine muds are deep-water deposits and that the formation of carbonaceous deposits requires reducing as opposed to oxidizing conditions, most of the hypotheses relating to black shale accumulation demand that deep, tranquil water is essential.

According to Marr (1925) the graptolite-shales of Europe were deposited in quiet embayments where the bottom was fouled by the presence of hydrogen sulphide and no life could exist. In a diagrammatic section, Marr shows that the benthonic forms develop in the littoral zone of the embayments where there is sufficient oxygen to maintain life, and the only fossils accumulated in the poisonous muds are the dead planktonic or pseudo-planktonic forms which sink from the surface.

This accounts for the pure graptolite fauna in which the benthonic forms are not associated, but Ruedemann suggests "occasional and incomplete incursions, or overflows, from a geosyncline" to account for the mixed faunas, such as that of the Utica shales of North America, which pass into limestones.

Clarke (1903) suggested that the black shales accumulated in deep almost stagnant seas, such as the present Black Sea, where there was only slight vertical circulation between two layers of different salinity, and Schuchert (1910) believes that they form in stagnant *culs-de-sac* or infill holes in the sea floor.

Neither of these theories accounts for the occasional mixed faunas or for the conglomerates and sandstones which are sometimes found interbedded with the black shales, and both Ulrich (1911) and Ruedemann (1897, 1911, 1934) have pointed out that the world-wide distribution of the graptolites and their dependence upon ocean currents for their distribution negative any theory requiring stagnant conditions, and furthermore, they discredit hypotheses requiring that the shales be deposited in narrow embayments or *culs-de-sac*, for they point out that the marine currents could not carry the plankton to the head of such a bay. It would, however, be possible for wind to carry the plankton into the bay, but the world-wide distribution of this fauna suggests that their preservation in such bays would be too limiting a condition. Ruedemann (1911) concludes that the world-wide distribution of some species shows that the Palaeozoic oceans were connected to permit intercommunication but sufficiently separated to permit the development of provincial characters. Ulrich and Ruedemann both consider that the occurrence of black, graptolite-bearing shale in the Levis, Athens and Ouachita troughs, which are narrow strips hundreds of miles in length, indicates that the shales were laid down in geosynclines open to the ocean at both ends. As mentioned above, Ruedemann accounts for the mixed faunas and the occasional admixture of littoral sediments by postulating an occasional break through of the barrier and the formation of epicontinental seas. He states, however, that "marine faunas are not found generally distributed through the mass of the black shales. They occur in occasional thin seams in which, however, their remains are likely to be very numerous, and the best of these—indeed it may be the only zone of such fossils in hundreds of feet of shales—is usually in the basal foot or two". He thinks that "not depth but tranquillity" is the main factor and that deposition probably takes place between the agitated water and the currentless sea. He suggests that the waters may have been stagnant or the circulation imperfect over long periods and that the marine life may have become extinct by fouling of the water.

Later, Ruedemann (1944) states, with reference to the shales of the Hudson Valley Belt, "the graptolite shales are black, very fine-grained sediments which were deposited at the lower slopes of continental shelves or at the bottom of the abysses, some at 12,000 + feet". He supports this hypothesis as to their deep origin by pointing out that radiolarian cherts may be found associated with black shales (Ruedemann and Wilson, 1936) and that the radiolarian genera are very deep-water forms.

Grabau and O'Connell (1917) claim that the black shales are deposited in the lagoons and bays of deltas where the plankton has been washed by exceptionally high tides and storms. They review the two classical areas for graptolite-bearing shales, namely, the Swedish deposits and those of Moffatdale in Scotland, and show that both indicate a progressive overlap accompanying a positive movement of the strand-line. They believe that the sediment is mainly of terrestrial rather than of marine origin and that the holo- or epi-plankton has been buried in the deltas or lagoons. This theory has not gained general acceptance, for though it accounts for shales of shallow water origin, it is difficult to believe that storms and exceptional tides could account for this widely distributed and common type of sediment.

Twenhofel (1915) suggests that the deposits may be connected with low temperatures where the decay of the plankton is retarded and where the conditions are too cold for the growth of the benthonic forms. Twenhofel wrote in 1915 "much has been written relating to the origin of black shales, but judging from the divergence of published opinion, no hypothesis has gained a general acceptance". The same statement can be made in 1945.

To gain general acceptance an hypothesis must account for the fine texture of the shales, for the not infrequent intercalations with coarse-grained sediments, for the occasional overlaps indicating shallow water deposition, for the elongated narrow strips hundreds of miles in length indicating geosynclinal deposition, for the world-wide distribution of some graptolites and the provincial development of others, for the general absence of benthonic forms and the occasional mixed faunas, the benthos usually being restricted to narrow seams often near the base of thick black shale deposits, and finally for the carbon content and the excellent preservation of the graptolites which indicates rapid burial and lack of oxidation.

2. *The Volcanic Ash Hypothesis.*

Studies in present-day mobile areas indicate that continental masses are often fringed by island arcs on which active volcanoes are situated. At the present time such festoon islands occur on the western shores of the Pacific Ocean and cut off comparatively tranquil seas from that ocean. On the eastern shores of the Pacific the volcanoes are situated on the main continental mass and the festoon islands are absent. Nelson pictured palaeogeographical conditions such as these in Ordovician times when he stated that the bentonite was derived from a volcano situated on an island off a peninsula separating the Lowville Sea from the Palaeozoic Atlantic. The great eruptions of Tomboro and Krakatau, cited above, took place in such a mobile area and both volcanoes are situated on islands. On the other hand, Katmai is situated on the mainland of Alaska, and Fenner (1925) has been able to trace great rifts in the Valley of Ten Thousand Smokes where much of the volcanic ash has accumulated.

As stated by Ulrich (1911) and Ruedemann (1911, 1934), the elongated masses of black shale extending over hundreds of miles must have been laid down in a geosyncline open at each end of the ocean to allow the ingress and egress of the oceanic plankton, and it is to be expected that volcanoes would be situated along the shores of such a great trough.

If large volumes of volcanic ash were suddenly poured on the masses of plankton floating either in an island-fringed sea or in a geosyncline, they would founder and sink. Their sudden burial provides the perfect conditions for the preservation of the graptolites and for the slow decomposition of the associated seaweeds cut off from all possibility of oxidation. Furthermore, if this load of ash and plankton chanced to fall on any benthos life in the littoral zone of the sea or geosyncline, then the benthos would immediately be killed and preserved as a seam at the base of the black shale deposit. In the course of time the benthonic forms would probably invade the shores again only to be killed off again by a further eruption from the same volcano or from others situated further along the shore or fringing arc.

Hypotheses suggesting the shallow water origin of the graptolite-shales have to depend upon severe storms and unusually high tides to sweep the plankton into the shallow bays or deltas, but such deposits could be synchronous with the laying down of the deeper water ash beds, for there is little doubt that the great volcanic outbursts would be accompanied by tidal waves which would sweep the continental shores, driving the plankton into the landlocked lagoons, where it would be immediately buried by volcanic ash. Thus overlaps on coarser deposits and intercalations of coarser sediments could be accounted for and formed either among delta deposits or along the littoral zones. Volcanic ash could therefore form accumulations of the same rock facies under apparently different environmental conditions.

In the case of the New South Wales rocks, it is suggested that the bulk of the material is rhyolitic ash or dust, since rhyolites are known to occur in the Upper Ordovician sequence at Cooma, and the composition of the siliceous slates appears to conform to that of certain rhyolites and rhyolitic tuffs; but it must be emphasized that rhyolitic material need not necessarily be the material that entombed the graptolites and that this hypothesis might be applied to shales of very different composition. Hence Twenhofel (1926) has shown that the bentonite is very different in composition from the rhyolitic ash from which it was derived, and a difference in composition could be caused either by subsequent alteration of the ash or by an original difference in the type of volcanic material ejected. Actually volcanoes emitting rhyolite are more often of the explosive type, and the acid type of material is more often associated with terrestrial volcanoes.

V. SUMMARY.

It has been shown that the graptolite-bearing slates of the Upper Ordovician in New South Wales are highly siliceous and that their siliceous nature is probably original. It is suggested that they may have been formed as the result of large accumulations of volcanic ash which encased the plankton and prevented oxidation of the carbon content.

This hypothesis for the origin of the graptolite-bearing black shales is considered in the light of other hypotheses and of the necessity to account for all the observed facts concerning black shale accumulation.

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